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Feather-edge of marine hydrate

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An irregular feather-edge and potential outcrop of marine gas hydrate along the Mauritanian margin

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26 **ABSTRACT**

27 The dissociation of marine hydrate that surrounds continental margins is thought to be
 28 an agent for past and future climate change. As the water depth decreases landwards, the
 29 base of the hydrate stability zone progressively shallows until hydrate occurs immediately
 30 below the seabed where an increase in bottom water temperature can cause dissociation. But
 31 the true extent of these most vulnerable hydrate deposits is unknown. Here we use
 32 exceptional quality three-dimensional (3-D) seismic reflection imagery offshore of
 33 Mauritania that reveals a rare example of a bottom simulating reflection (BSR) that intersects
 34 the seabed and delineates the feather-edge of hydrate. The BSR intersects the seabed at the
 35 ~636 m isobath but along the 32 km of the margin analysed, the intersection is highly
 36 irregular. Intersections and seismic evidence for hydrate less than ~ 4.3 m below the seabed
 37 occur in seven small, localised areas that are 0.02 - 0.45 km² in extent. We propose gas flux
 38 below the dipping base of the hydrate to these places has been particularly effective. The
 39 intersections are separated by recessions in the BSR where it terminates below the seabed,
 40 seaward of the 636 m isobath. Recessions are areas where the concentration of hydrate is
 41 very low or hydrate is absent. They are regions that have been bypassed by gas that has
 42 migrated landward along the base of the hydrate or via hydraulic fractures that pass vertically
 43 through the hydrate stability zone and terminate at pockmarks at the seabed. An irregular
 44 feather-edge of marine hydrate may be typical of other margins.

45

46

47 **Keywords:** hydrate; seabed; dissociation; warming; reflection; gas

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51 1. Introduction

52

53 Marine gas hydrate is a solid compound of water and gas that occurs in many settings,
54 including sediment surrounding deep water continental margins. The stability of hydrate is
55 related to temperature and pressure (P-T) and in these settings the progressive landward
56 reduction in water depth causes the base of the gas hydrate stability zone (BHSZ) to shallow
57 and intersect the seabed. This configuration results in a potential hydrate zone that thins in a
58 landward direction (Dickens, 2001; Milkov and Sassen, 2000) that has been termed the
59 feather-edge of marine hydrate (Fig. 1A; Ruppel, 2011).

60

61 The feather-edge holds ~3.5% (Ruppel, 2011) of the estimated $\sim 7 \times 10^2$ - $\sim 1.27 \times 10^4$ Gt
62 of carbon held in marine hydrates (Dickens, 2011). Where the BHSZ intersects the seabed,
63 hydrate may occur at the sediment-water interface (e.g. Egorov et al., 1999) or because of the
64 anaerobic oxidation of the methane, just below it (Barnes and Goldberg, 1976). Past, rapid
65 climate perturbations have been attributed to several different phenomena, including the
66 dissociation of marine hydrate (Dickens et al., 1995). Warming of the seabed in the feather-
67 edge domain could cause dissociation after only a few decades, because of the proximity of
68 the hydrate to the seabed (Thatcher et al., 2013). Dissociation could even be seasonal (Berndt
69 et al., 2014) or associated with changes in seabed temperature caused by upwelling currents
70 (see Hagen, 2001). Methane release has been documented at the feather-edge of marine
71 hydrate offshore of Svalbard (Westbrook et al., 2009; Berndt et al., 2014) and the eastern
72 North American margin (Phrampus and Hornbach, 2012; Skarke et al., 2014).

73

74 Although hydrate dissociation has long been proposed as a mechanism for climate
75 change (e.g. Dickens et al., 1995) and there is potential evidence for dissociation on some

76 margins, descriptions of the feather-edge using seismic reflection data lack detail (Ben-
77 Avraham et al., 2002; Coffin et al., 2011; Phrampus and Hornbach, 2012). This is because
78 they are based upon widely spaced two-dimensional (2-D) seismic lines and there are no
79 borehole calibrations. Key questions remain; for instance, regarding the amount of hydrate
80 that is vulnerable, whether it occurs consistently along continental margins and how gas
81 migrates to sustain it. Here we provide the first 3-D seismic description of the feather-edge
82 of marine hydrate, based upon the mapping of a BSR that intersects the seabed. We describe
83 the evidence for outcropping of hydrate and consider how gas sustains hydrate in these
84 settings.

85

86 **2. Hydrate and the Feather-Edge**

87

88 In addition to P-T conditions, hydrate formation is controlled by the concentration of
89 dissolved gas, which needs to be higher than its solubility in pore water (Xu and Ruppel,
90 1999). The BHSZ can coincide with the base of a hydrate accumulation, although this is not
91 necessarily the case (Xu and Ruppel, 1999) and it may or may not be marked by a BSR (e.g.
92 Dillon, et al., 1980).

93

94 BSRs in hydrate provinces, including this one, are recognized as high-amplitude,
95 negative polarity reflections, usually caused by the velocity contrast between sediment
96 partially saturated with hydrate above it and sediment partially saturated with free gas below
97 it (Field and Kvenvolden, 1985). The minimum saturation of hydrate in sediment required to
98 cause a moderate or significant increase in acoustic impedance is unclear. It could be as little
99 as 2% (Helgerud et al., 1999), 14% (Hu et al., 2014) or in excess of 40% (Carcione and
100 Tinivella, 2000). The saturation of hydrate within the hydrate stability zone can be highly

101 variable, with the highest saturations often occurring in porous sands, permeable layers and
102 faults (e.g. Malinverno et al., 2008). This heterogeneity may be one of several factors that
103 determine how the hydrate manifests itself where it outcrops at seabed.

104

105 We define the feather-edge of gas hydrate, also referred to as the hydrate wedge
106 (Gorman and Senger, 2010), as the region where the BHSZ starts to shallow and intersects
107 the seabed because of a progressive landward reduction in water depth (Fig. 1A). Since
108 hydrate formation and dissociation are closely linked to the ambient P-T conditions, the
109 intersection should be at a consistent depth along the margin, often ~300 - 600 m (e.g.
110 Milkov and Sassen, 2000). But this is also dependent on the composition of hydrocarbons in
111 the hydrate with the shallower intersections occurring where methane is accompanied by
112 other hydrocarbon gases (Milkov and Sassen, 2000). Seaward of the intersection, hydrate
113 could exist at the seabed (e.g. Egorov et al., 1999; MacDonald et al., 1994) in an outcrop
114 zone (Fig. 1A).

115

116 Evidence for the feather-edge of marine gas hydrate has been detected using 2-D
117 seismic data for example on the margins of South Africa (Ben-Avraham et al., 2002 – e.g.
118 their figure 2) and Chile (Coffin et al., 2011) the North Island of New Zealand (Crutchley et
119 al., 2010). Off West Svalbard, there is evidence for a feather-edge on the basis of gas flares
120 that occur only landward of the 396 m isobath (Chabert et al., 2011; Sarker et al., 2012;
121 Westbrook et al., 2009). In the northwest Black Sea, Naudts et al. (2006) described gas
122 plumes that occur landward of the 725 m isobath and similar observations are also made off
123 the northern US Atlantic margin (Skarke et al., 2014).

124

125 In terms of how gas migrates to the landward limit of marine hydrate, at the West
126 Svalbard feather-edge, Thatcher et al. (2013) proposed that gas migrates vertically through
127 fractures toward the BHSZ; laterally within seaward-dipping permeable strata or along the
128 base of the hydrate. At this feather-edge, carbonates at gas seeps indicate venting has been
129 occurring for > 3000 yrs. (Berndt et al., (2014). Large-scale 2-D modelling of the feather-
130 edge on this margin shows that warming could cause methane release near the landward limit
131 of the top of the hydrate stability zone (Reagan and Moridis, 2009).

132

133 3. Seismic Data and Geological Setting

134

135 The offshore Mauritania 3-D seismic survey was processed by several steps including
136 multiple suppression and post-stack time migration. The dominant frequency of this data at
137 the depth of the hydrate is ~50 Hz. The typical seismic velocity at the depth of investigation
138 is ~1700 ms⁻¹ and therefore 100 milliseconds two-way-travel time (ms TWT) on seismic
139 sections is equivalent to approximately 85 m. The final bin spacing of the seismic grid is 25
140 × 25 m. The data are minimum phase and a negative acoustic impedance contrast is
141 represented as a black-red (negative polarity) reflection. Amplitude maps are all root mean
142 square (RMS – see Brown, 2010) on the reflection itself, rather than over a time window.

143

144 In the study area the seabed dips at ~1° (Fig. 1B) and the BSR generally dips at an
145 angle of ~2.3°. This increases as it shallows from 200 mbsf (meters below seafloor) to
146 intersect the seabed at a seabed intersection depth (SID) of 636 m (Fig. 1C). We have not
147 identified evidence for an opal-A to opal-CT diagenetic BSR in the dataset, which can occur
148 at similar depths below seabed, but in contrast gives rise to a red-black reflection (trough-
149 peak, positive polarity) reflection (see Davies and Cartwright, 2002). Below the BSR, at least

150 368 vertical seismic chimneys (e.g. Fig. 2A) are observed in the data by Davies and Clarke
151 (2010) and interpreted as networks of hydraulic fractures that allow for the vertical migration
152 of pore fluid and gas. Most of the chimneys terminate at or below the BSR.

153

154 The margin has several proven oil and gas accumulations and we do not have data on
155 the gas composition of the hydrate. Hydrocarbon exploration wells in the area of the 3D
156 seismic data (Chinguetti V1 and Chinguetti-6-1 – Fig. 1B) show that the sediment hosting the
157 hydrate and the BSR probably span the last 5.2 Ma (Vear, 2005) and scientific drilling 150
158 km to the north (Henrich et al., 2010) indicates that in a similar setting fine-grained turbidites
159 and foram-nannofossil hemipelagites were deposited. Industry geotechnical data from an
160 area 100 km to the south, acquired at similar water depths, provides additional information on
161 the seabed temperature (Lane, 2005). Measurement of water temperature at a 500 m water
162 depth shows a mean temperature variation of 9.6 °C to 10.5 °C, over the five month period
163 between August and December 2002. Lane (2005) also reports the measured sediment
164 temperatures at four sites between 539 - 800 m were cooler than the water column at
165 equivalent depths. An upwelling undercurrent fed by South Atlantic Cold Water (SACW)
166 feeds a belt of upwelling along the margin (Hagen, 2001).

167

168 **4. Description of the BSR**

169

170 *4.1 Bands of High Seismic Amplitude at the BSR*

171

172 The general shape of the BSR is revealed by contours of its depth below sea level
173 superimposed on the RMS seismic amplitude map of the reflection and shows that it has a
174 curved (concave downward) form that shallows landward (Fig. 1C). The map reveals

175 continuous and semi-continuous bands of high seismic amplitude that are 0.5 – 1.5 km wide
176 and up to 30 km in length. Here we analyse two examples (areas marked by white boxes in
177 Fig. 1C) which have variable geometries and orientations relative to the strike of the BSR
178 (Fig. 1B and C). Most of the bands terminate without reaching the 636 m isobath (Fig. 1C).
179

180 The first example (Fig. 2C) consists of nine high-amplitude bands (marked I to IX -
181 Fig. 2AB). They are east-west and southwest-northeast orientated (Fig. 2AB). A
182 representative seismic cross section shows that they are negative-polarity reflections (the
183 opposite to the seabed reflection) and occur immediately down-dip from where these
184 reflections intersect the BSR. The intersections are coincident with possible phase reversals
185 (Fig. 2B inset). The differential relief for an individual band is up to 600 m, although they
186 may not be continuous and connected along their entire length (Fig. 2A).

187

188 In the second example a single band of high seismic amplitude is up to 2 km wide and
189 12 km long (Fig. 3AB). Again it corresponds to a negative polarity reflection at the
190 interpreted level of the BSR (Fig. 3AB). The northern boundary to the band is a line of
191 intersection (see Davies et al., 2012) that marks where the high-amplitude reflection
192 intersects the BSR (marked by the yellow dot in Fig. 3B). The BSR is also characterised by
193 regions where there are no distinctive bands of high seismic amplitude (Fig. 1C). These areas
194 occur where there is concordance between the BSR and stratal reflections or where
195 reflections have been disrupted due to slope processes (e.g. slope failure outlined in Fig. 1C).

196

197 *4.2 Steps in the BSR*

198

199 The BSR shallows either gradually or in a series of steps (Fig. 4A-D). The steps are
200 regions where the BSR is locally concordant with stratal reflections. They are separated by
201 narrower regions where the BSR cross-cuts them (Fig. 4). The steps are 0.5 - 3 km wide and
202 up to 9 km long. The shallowest one (marked step 1 in Fig. 4B) occurs where the negative
203 polarity BSR reflection is immediately below the seabed reflection (positive polarity). Step 1
204 does not extend along the entirety of the feather-edge but occurs locally in 5 places (encircled
205 by dashed black lines - Fig. 4A). A seismic line that transects two of these areas (Fig. 4C)
206 shows that there are clear gaps in the BSR reflection with the lateral terminations of the BSR
207 being marked by phase reversals (marked by yellow circles in Fig. 4C).

208

209 We predicted the position of the BHSZ at steady state by using the hydrate stability
210 curve for pure methane given by Moridis (2003) with a correction for sea water salinity of
211 35 wt% (see methodology of Davies et al., 2012). The stepped geometry of the BSR
212 approximately follows the curved form predicted for the BHSZ (blue dashed line in Fig. 4D;
213 see Gorman and Senger, 2010).

214

215 *4.3 Intersection of the BSR with the Seabed*

216

217 We mapped the intersections along 32 km of the margin. The landward extent of the
218 BSR is highly irregular and there is no continuous intersection between the BSR and the
219 seabed. Instead intersections occur over very restricted sections of the seabed along the 636
220 m isobath (Fig. 4A and B). Between these intersections there are gaps in the BSR (herein
221 termed recessions - see Figs 1, 3-6) where it terminates below rather than at the seabed. In
222 these localities there are no anomalous high-amplitude reflections that could be indicative of

223 increased acoustic impedance, which would be consistent with high hydrate saturations
224 (Carcione and Tinivella, 2000).

225

226 Approximately circular pockmarks occur on the seabed where there are recessions in
227 the BSR and in some places, landward of the SID (marked with red and black circles and
228 labelled 1, 2 and 3 on Fig. 5BC). In contrast there are no circular features of this kind on the
229 seabed above the mapped BSR (Fig. 5A). They are 100 - 400 m wide. Below the seabed
230 pockmarks are vertical seismic chimneys that extend for 300 - 600 m (marked by black
231 arrows – Fig. 5C). Some of the bases of these chimneys emanate from high-amplitude
232 reflections (Fig. 5ABC). The seabed dip map (Fig. 5A) has an uneven relief above the
233 mapped BSR.

234

235 Similar observations of pockmarks immediately landward of the feather-edge, based
236 upon bathymetry data acquired in 2003, have been made 100 km to the South of this study
237 area (Lane, 2005). They are 60 - 800 m in diameter and occur within a north – south
238 orientated area between the 540 – 640 m isobath. Hard calcareous accretions, which may
239 represent authigenic carbonates, were recovered from a shallow core from one of the
240 pockmarks (Lane, 2005).

241

242 Step 1 is the shallowest of the four steps and is immediately below the seabed. It is
243 not perfectly concordant with stratal reflections. Instead, the BSR reflection shallows
244 gradually in a landward direction (Fig. 6B) until, at its eastern end, there is a reduction in the
245 amplitude of the seabed reflection (Fig. 6C). This is coincident with doming of the seabed
246 reflection. Similar changes in reflection amplitude are detected in six other places along the
247 636 m isobath on an RMS amplitude map of the seabed (Fig. 6A). On seismic sections, the

248 seabed and BSR interfaces should still be resolved when the distance between them is $\sim 1/4$ of
249 the seismic wavelength. At $\sim 1/8$ of the wavelength the interference of the two reflections
250 will cause a reduction in seismic amplitude (see Widness, 1973). Using a sediment velocity
251 of 1700 ms^{-1} and a frequency of the seismic data of 50 Hz, we estimate $1/8$ of the wavelength
252 to be a distance of $\sim 4.25 \text{ m}$ (see Widness, 1973). Therefore, the hydrate-gas interface is
253 $\sim 4.25 \text{ m}$ below the seabed. The seven places on the eastern margin of step 1 where these
254 characteristics are observed have areas of between $0.02 - 0.45 \text{ km}^2$ (Fig. 6B).

255

256 **5. Interpretation**

257

258 *5.1 High-amplitudes at the BSR*

259

260 The bands of relatively high seismic amplitude are negative polarity reflections which
261 is the opposite polarity to the seabed reflection (e.g. Fig. 3B). Phase reversals are also
262 coincident with the intersections of these reflections with the BSR (Fig. 2B). As the bands
263 occur at the BSR, their amplitude depends on the velocity and density of the hydrate and sub-
264 hydrate sediment. A strong negative polarity reflection is probably caused by the transition
265 from hydrate-saturated sediment to sediment containing some free gas as this would create
266 the necessary decrease in acoustic impedance (Domenico, 1977; Carcione and Tinivella,
267 2000). When taken together, the observations are consistent with the bands of high seismic
268 amplitude representing free gas that is sealed by hydrate-saturated sediment at the BSR (e.g.
269 Chabert et al., 2011).

270

271 Davies et al. (2012) proposed that the bands form as a result of upward resetting of
272 the BHSZ, driven by sedimentation, which leads to the dissociation of hydrate. The

273 characteristic width of 0.5 to 3 km is therefore related to the angle of the intersection and the
274 magnitude of the last upward shift in the BHSZ (i.e. narrow bands would form where there is
275 a high angle of intersection and a small upward shift in the BHSZ). Although the bands
276 appear on the amplitude maps to have a vertical relief of up to ~600 m (e.g. band XII – Fig.
277 2A), they are unlikely to represent fully interconnected reservoirs of free gas as the pore
278 pressure at the shallowest terminations would exceed lithostatic pressure (Davies and Clarke,
279 2010 - their figure 4).

280

281 In fine-grained sediments, horizontal permeability is often several times that of the
282 vertical permeability (e.g. Ayan et al., 1994; Yang and Aplin, 2007). Where the bands are
283 parallel to the dip of the BSR, the configuration provides relatively high permeability
284 migration routes for gas sealed below the hydrate-saturated sediment. When they are parallel
285 to the strike of the BSR, the configuration is less conducive for up-dip migration of gas below
286 the BSR. Disruptions in bedding, caused by slope failures would also impede up-dip
287 migration of gas (Fig. 1C).

288

289 The vertical seismic chimneys (Fig. 2A) are generally interpreted to be evidence for
290 clusters of hydraulic fractures (Zuhlsdorff and Spieß, 2004), suggesting vertical migration of
291 gas has occurred to the base of the feather-edge of the hydrate, as predicted elsewhere
292 (Thatcher et al., 2013; Westbrook et al., 2009).

293

294 *5.2 Variable Extent of Feather-Edge*

295

296 The map of the BSR reveals recessions where the BSR does not intersect the seabed.
297 In these recessional areas, the negative polarity BSR switches abruptly to a positive polarity

298 reflection (Fig. 4C). These areas could be where hydrate saturations are high enough to
299 provide an effective seal for free gas, but no free gas is present. This could be because gas has
300 not migrated to these localities, or is present but not in high enough saturations to exceed the
301 solubility of methane in pore water (Xu and Ruppel, 1999; Haacke et al., 2007).
302 Alternatively concentrations of hydrate could be too low to provide an effective seal for free
303 gas. It is also plausible that the vertical clusters of hydraulic fractures allow gas to bypass the
304 hydrate stability zone.

305

306 Seabed venting of free gas has sometimes been a proxy for the landward extent of
307 hydrate at the feather-edge (Naudts et al., 2006; Westbrook et al., 2009). Although gas
308 chimneys often penetrate hydrates (Wood et al., 2002) and reach the seabed (Liu and
309 Flemings 2006), in this dataset, the occurrence of chimneys that penetrate the BSR are rare
310 (Davies and Clarke, 2010) and we do not detect any seabed pockmarks above the BSR. 100
311 km to the south, pockmarks only occur landward of the 640 m isobath (Lane, 2005) and
312 landward of the 636 m isobath in this survey. This is where hydrate in the sediment is absent.
313 Therefore our preferred interpretation of the recessions is that they are areas where hydrate
314 concentrations are low enough for there to be no effective seal for free gas, so no BSR is
315 imaged and venting via pockmarks occurs.

316

317 *5.3 Seismically Imaged Outcrop Zone*

318

319 The steps are strata-parallel and approximately follow the predicted position of the
320 BHSZ (Fig. 4D). This is consistent with sediment properties being a major factor controlling
321 the distribution of gas hydrates and therefore also the free gas sealed by the hydrate in the
322 sediment. For instance, hydrate concentrations tend to be higher in coarse-grained, more

323 porous sediments (Malinverno, 2010; Weinberger et al., 2005), which would provide a more
324 effective seal for free gas. We interpret steps to form because hydrate concentrations are
325 higher in more porous strata. We are unclear as to why it should occur in one part of the
326 survey and not throughout it.

327

328 At the landward end of step 1 the characteristic positive polarity seabed reflection is
329 located immediately above the negative polarity BSR reflection (Fig. 6B). The change in
330 reflection character of the seabed (Fig. 6C) is probably due to tuning of the two reflections.
331 When the thickness between the seawater-seabed interface and hydrate-free gas interface is
332 less than $\sim 1/4$ of the wavelength $\lambda/4$ (~ 8.5 m), two reflections will no longer be resolved.
333 When the thickness is $\sim 1/8$ of the wavelength, the amplitude of the seabed reflection should
334 decrease as a result of destructive interference between the reflections from the two interfaces
335 (Widness, 1973). Where we observe a drop in amplitude (Fig. 6C) we predict that in these
336 locations free gas is ponding only $\sim 1/8$ of the wavelength (~ 4.3 m) below the seabed and the
337 hydrate can be no thicker than this. The slight mounding of the seabed coincident with the
338 drop in amplitude (Fig. 6C) would be consistent with hydrate occurring at the seabed itself.
339 Alternatively the response is related to carbonates at the seabed, but one would expect there
340 to be an increase in seabed amplitude rather than a reduction. However, without direct
341 evidence, such as video footage or drop cores we cannot be certain that there is hydrate at the
342 sediment-water interface and hence term this a 'seismically defined' outcrop zone.

343

344 **6. Discussion**

345

346 *6.1 Gas Migration to the Feather-Edge*

347

348 The observations support several mechanisms by which gas migrates to the feather-
 349 edge. Advection through hydraulic fractures which are manifested as vertical seismic
 350 chimneys (Zuhlsdorff and Spieß, 2004) is one mechanism (Davies and Clarke, 2010; Davies
 351 et al., in review). Gas could either be incorporated into the hydrate or pond below the
 352 hydrate, if the pore fluid is super saturated with respect to gas (Haacke et al., 2007). We
 353 propose some gas migrates along the base of the hydrate and that this occurs dominantly
 354 within regularly-spaced, relatively high permeability beds that intersect the BSR. Where
 355 lines of intersection are parallel to the dip of the seabed and BSR they are orientated
 356 favourably for gas migration to the feather-edge of the hydrate. Gas could also migrate along
 357 the base without being confined to these higher permeability channels, by diffusive flow.
 358 The gently curved (concave downward) and dipping geometry of the BSR, creates a natural
 359 focus for gas migrating along its base, towards the few places where a BSR does intersect the
 360 seabed (Fig. 1C).

361

362 *6.2 Dissociation of the Feather-Edge*

363

364 The seven areas where we interpret hydrate to be located within 4.3 m of the seabed
 365 are ~ 0.02 to ~ 0.45 km² in area. Collectively, they represent an area of 0.85 km² (Fig. 6A).
 366 Given that the hydrate is ≤ 4.3 m in thickness across these regions the maximum volume of
 367 sediment containing hydrate at or immediately below the seabed (within 4.3 m) is ~ 0.0037
 368 km³. If step 1 existed along the entire study area (32 km in length) and the outcrop zone is
 369 200 m wide and the hydrate is 4.3 m thick, then the total volume of sediment saturated with
 370 hydrate would be 0.0275 km³. However, because outcrop zones are localised, the volume of
 371 hydrate-saturated sediment at or immediately below the seabed is a small fraction of this
 372 (0.0037 km³). If warming of ocean currents occurs in the future, the time taken for thermal

diffusion, hydrate dissociation, and gas migration, could be only a matter of decades (Thatcher et al., 2013), but because the outcrop zones are so localised the initial volumes of gas released would be modest initially and increase as deeper, more continuous areas of the hydrate were effected. The role that upwelling of cold water fed by the SACW could have in changing seabed temperature and therefore the stability of hydrate remains a key question.

7. Conclusions

The feather-edge of marine hydrate is rarely observed. In this example, the landward extent of the feather-edge of marine gas hydrate is irregular. Hydrate occurs at the seabed or immediately below it in very small, localised areas immediately seaward of the 636 m isobath. Hydrate is probably sustained here by migration of gas within favourably orientated relatively high permeability strata sealed by the overlying hydrate. An irregular feather-edge of marine hydrate may be typical of other margins.

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FIGURE CAPTIONS

398

399 Figure 1 A: Schematic of the feather-edge region and outcrop zone, showing positions of
 400 three hypothetical BSRs (1, 2 and 3) shifting as a response to warming of the seabed. SID –
 401 seabed intersection depth and PoI – point of intersection (in this and subsequent figures).
 402 Inset – schematic graph of temperature (T) against depth (D) for when the BSR is located at
 403 position 3, showing the hydrate stability curve (HSC) and temperature curve (TC). SB –
 404 seabed and OZ – outcrop zone on this and subsequent figures. B: Map of the seabed in
 405 metres, imaged by the 3-D seismic dataset. Inset – location map for the study area. C: RMS
 406 seismic amplitude map of the BSR showing bands of high seismic amplitude and localised
 407 intersections of the BSR with the seabed at the SID. Dashed yellow lines – depth contours
 408 for the BSR relative to sea level.

409

410 Figure 2 A: RMS amplitude map of the BSR showing high-amplitude bands (I-IX). LoI –
 411 line of intersection (in this and subsequent figures). B: Seismic line across high-amplitude
 412 bands showing they occur at the intersection of stratal reflections with the BSR. Red dashed
 413 line in this and subsequent figures – BSR.

414

415 Figure 3 A: Representative seismic line A-A' along a band of high seismic amplitude that
 416 intersects the BSR. Arrows mark the location of the BSR. Vertical full black line marks the
 417 change in orientation of the seismic line. Vertical black dashed line marks the intersection
 418 with line B-B'. Inset – 3-D schematic representation of high-amplitude bands at the BSR. B:
 419 Seismic line B-B' across a band of high seismic amplitude. Vertical black dashed line marks
 420 the intersection of seismic line A-A'. Dashed white lines – high-amplitude bands located at
 421 and below the BSR. Inset – RMS amplitude map showing the location of lines A-A' and B-
 422 B'. Red dashed line – interpreted position of the BSR. Black, white, yellow and red dots in

423 A and B mark the extent of the high-amplitude band in map view and seismic cross section.

424 Small insets – contrasting reflection character between the positive polarity and negative

425 polarity seabed and BSR reflections.

426

427 Figure 4 A. RMS seismic amplitude map of the BSR in the area where it intersects the

428 seabed. Outlined regions correspond to steps in the BSR. Areas encircled with black dotted

429 line – seven locations where step 1 identified. B: Representative seismic line (B-B') across

430 the feather-edge of the hydrate. C: Representative seismic line (C-C') across the hydrate.

431 Yellow circles mark phase reversals. SB – seabed; FG – free gas; GH – gas hydrate; AB –

432 acoustic blanking. D: Seismic line B-B' showing the modelled and interpreted BSR

433 intersecting the seabed.

434

435 Figure 5 Dip magnitude map of the seabed. Grey colours correspond to 1° dip, with lighter

436 and darker shades representing very small changes in dip. White line – landward extent of

437 the BSR. Red circles – pockmarks in the seabed. B: Zoom-in of part of the map in A.

438 Yellow and black dots – lateral extent of the BSR with corresponding locations marked the

439 representative seismic in C. Red circles – pockmarks (marked 1, 2 and 3). C: Representative

440 seismic line across a recession in the BSR. Black arrows – vertical seismic chimneys. Black

441 circles marked 1, 2, and 3 – three seabed pockmarks that correspond to those marked on B.

442

443 Figure 6 A: RMS amplitude map of the seabed. Dashed white line – the landward extent of

444 the BSR. Orange area – places where there is evidence for a reduction in seismic amplitude

445 of the seabed reflection consistent with hydrate immediate below or at seabed. Inset - seismic

446 line A-A' across the SID.

447

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Highlights:

- We provide the first description of the feather-edge of marine hydrate using three-dimensional seismic data.
- The landward extent of it, offshore of Mauritania is irregular and this may be typical for other margins.
- Hydrate that occurs at or below the seabed is rare along the margin.

Figure

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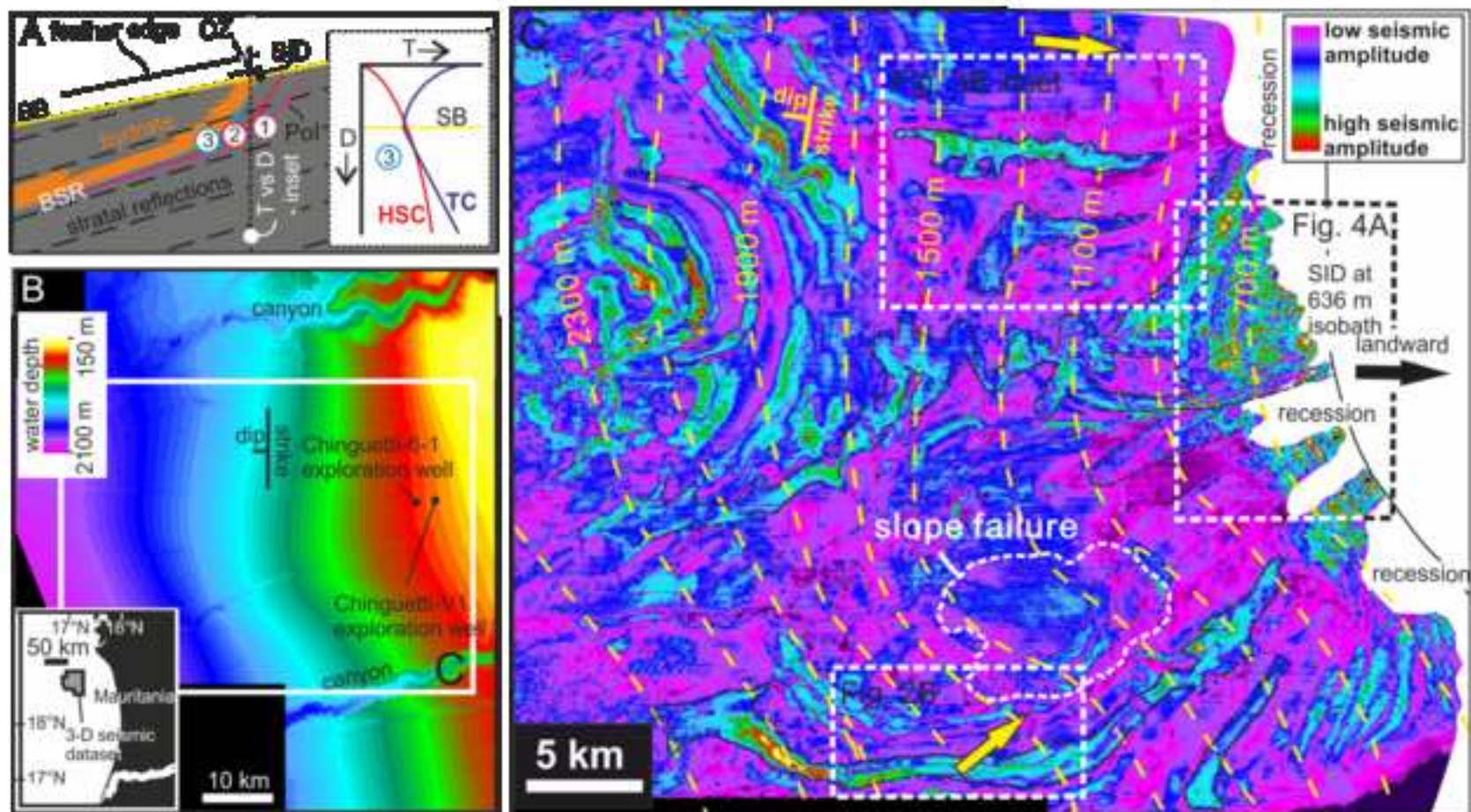
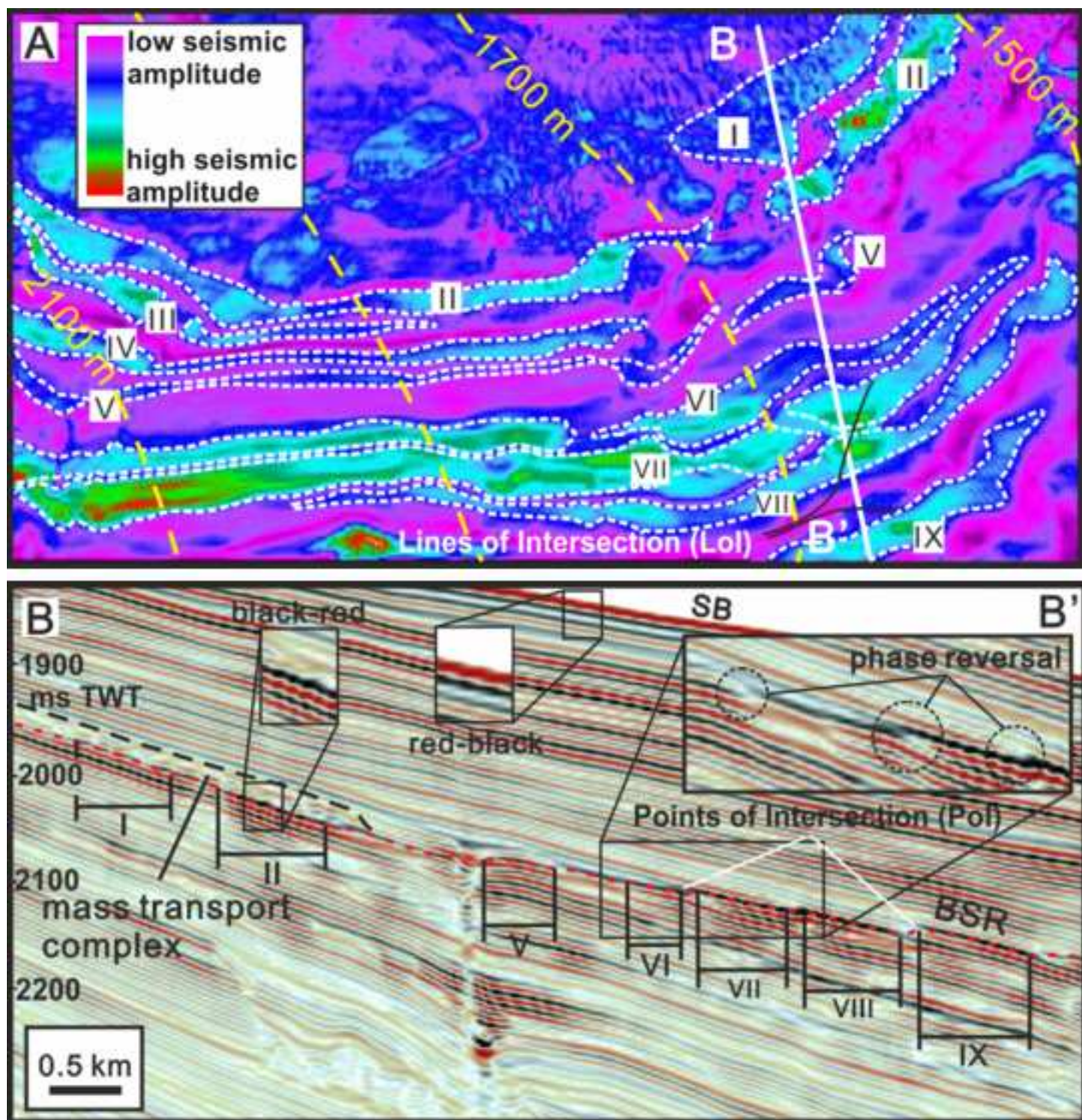
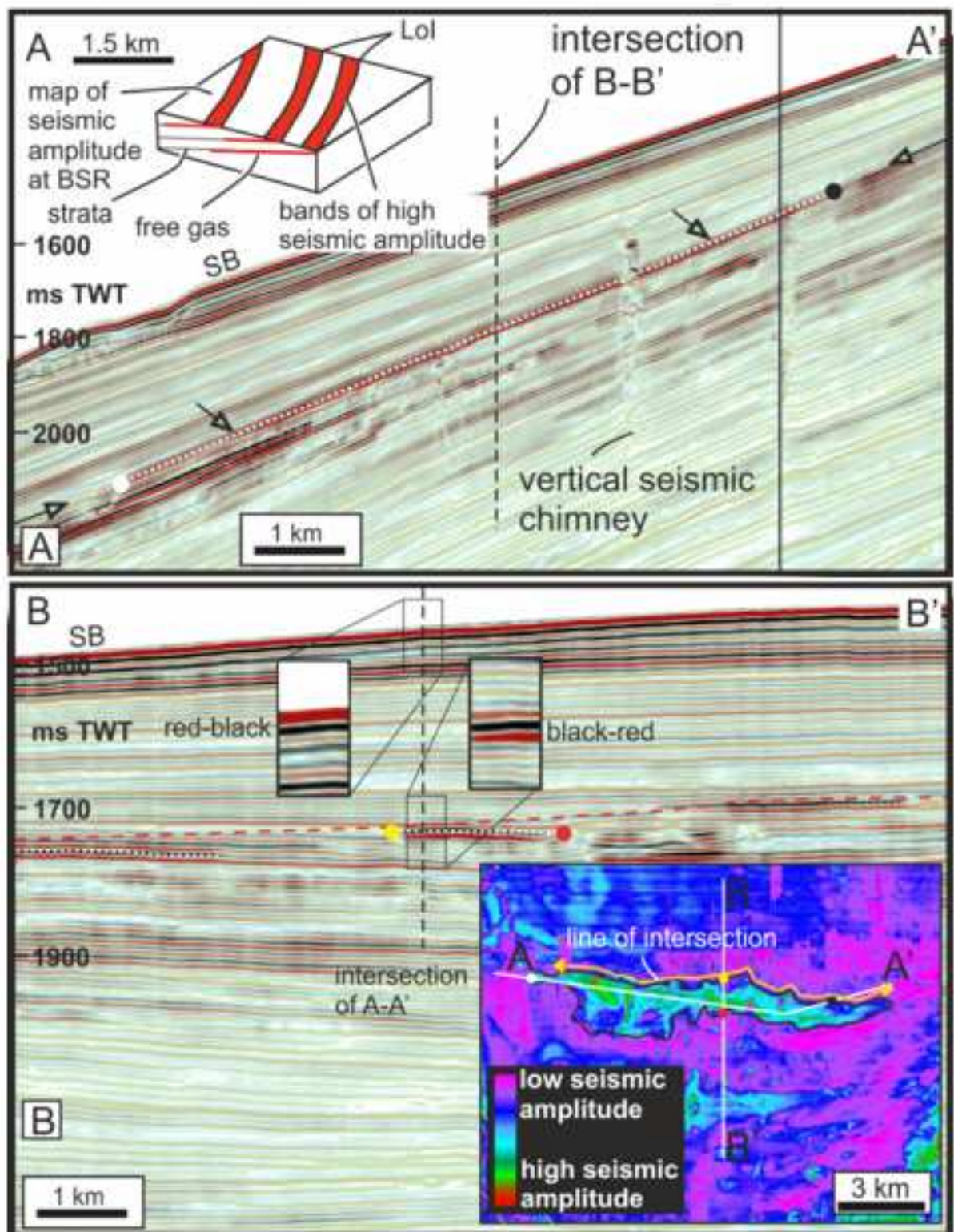


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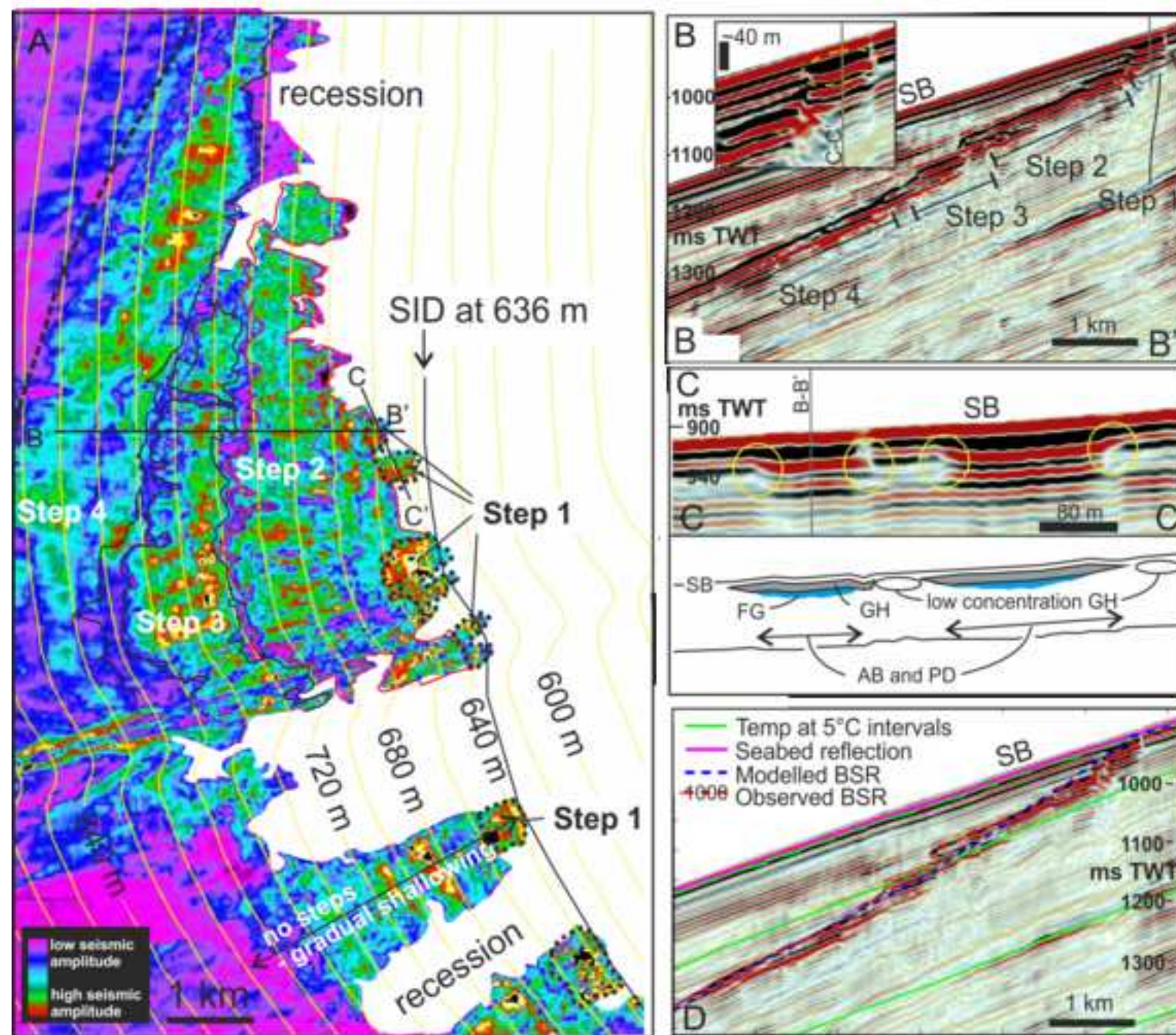
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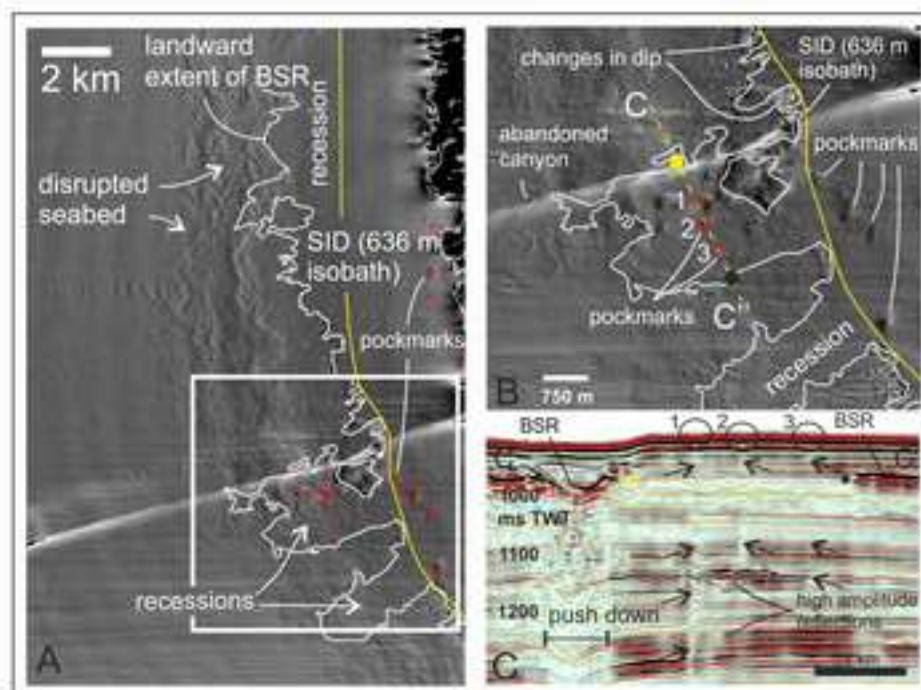


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